RESEARCH PAPER

THE CHANGING CLIMATE OF KIELCE: INSIGHTS FROM EXTENDED METEOROLOGICAL ANALYSES

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ABSTRACT. The study examined air temperature and monthly precipitation totals recorded between 1966 and 2023 at the hydrological and meteorological station of the Institute of Meteorology and Water Management (IMWM) in Kielce-Suków and the Copernicus Climate Change Service Climate Data Store (CDS). Based on these data, thermal and precipitation classifications were developed, supplemented by an extended assessment of snow cover duration in the Kielce region.

The results confirm a clear warming trend, reflected in an increasing number of warmer-than-average months and a decline in colder ones. The mean annual temperature has risen by approximately 0.03°C per year (0.33°C per decade), amounting to 1.62°C over the entire study period. Projections suggest an additional increase of approximately 1°C by 2030.

Snow cover conditions exhibited substantial variability. The mean number of days with snow cover (≥1 cm) was 63, ranging from 7 days in 2020 to 114 days in 1969, indicating a decline in recent decades. Average winter snow depth (December–March) was 4.84 cm, with extreme values recorded in 2020 (0.07 cm) and 1970 (23.4 cm). Maximum annual snow depth varied between 4 cm (2020) and 55 cm (1970). The mean duration of persistent snow cover (≥30 days) was 45 days, with a maximum of 88 days in 2006.

Precipitation patterns did not show a consistent long-term trend comparable to temperature. While summer months (June–August) still receive the highest totals, their temporal distribution is shifting. Some months (e.g., July, September) exhibit decreasing precipitation, whereas others (e.g., August, December) show increasing or no clear tendencies. The observed annual and seasonal variability is likely to intensify under ongoing climate change.

These findings underscore important implications for local ecosystems, agriculture, and water resource management, highlighting the need for adaptive strategies in the Świętokrzyskie region.

KEYWORDS: climate change, Kielce, air temperature, snow cover, precipitation

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INTRODUCTION

In urban areas, rising air temperatures are intensified by the urban heat island effect, driven by the dominance of paved and asphalted surfaces and the limited presence of dense vegetation. These materials absorb and retain heat, thereby increasing urban air temperatures (EPA 2025). Impermeable surfaces also restrict natural rainfall infiltration, which enhances the risk of flash floods during intense precipitation events (Pappalardo et al. 2023). Reduced greenery and permeable ground accelerate surface runoff into drainage systems that often lack sufficient capacity, exacerbating flood hazards and placing additional pressure on urban ecosystems (Fahy et al. 2019; Sohn et al. 2020; Szeląg et al. 2024).

Recent research increasingly highlights regional manifestations of global climatic processes. Although numerous studies address climate variability in Poland, long-term assessments specific to the Świętokrzyskie region remain limited. This study seeks to fill this gap by analyzing nearly six decades of air temperature, precipitation, and snow cover data from the Kielce-Suków station.

The transitional position of the Kielce region between lowland and upland areas makes it a valuable case study for understanding climate variability in Central Europe. Contemporary climate research focuses strongly on identifying trends and extremes in air temperature and precipitation, which are key determinants of environmental conditions and the functioning of natural systems. These changes are evident at both global and regional scales, influencing landscapes, hydrology, agriculture, and natural as well as urban ecosystems (IPCC 2023; Malhi et al. 2020).

In Poland, as in other parts of Central Europe, systematic increases in mean annual temperature and shifts in precipitation patterns have been documented in numerous climatological studies (Miętus et al. 2022; Wibig and Jakusik 2012). The Świętokrzyskie region, located in southeastern Poland, is particularly suitable for such analyses due to its varied terrain, diverse land use structure, and the presence of local climatic factors (Twardosz and Kossowska-Cezak 2016). The long-term operation of the IMWM meteorological station in Kielce-Suków provides a robust dataset enabling the evaluation of climatic changes in this area.

The examination of air temperature and precipitation from this station fits within broader research on the climatic regionalization of Poland (Lorenc 2000; Piotrowicz 2003), assessments of the frequency and intensity of extreme events (Kundzewicz et al. 2016), and studies on the impacts of climate change on water management and ecosystems (Kozłowska-Szczęsna et al. 1997; Ziernicka-Wojtaszek 2019). Climatic changes affect water balance and agroclimatic conditions, as well as the dynamics of natural and cultivated plant communities (Podgórska and Szwed 2017; Jarzyna et al. 2017), modifying the length of the growing season and increasing drought risk (Szwed et al. 2010; Chmielewski and Rotzer 2001).

The aim of this article is to characterize changes in air temperature and precipitation in the Świętokrzyskie region based on data from the IMWM Kielce-Suków station for the years 1966–2023. The analysis uses long-term time series to assess seasonal and annual variability of meteorological parameters, identify trends, and determine potential phenological shifts. Particular attention is given to the possible regional and environmental implications of the observed changes.

MATERIALS AND METHODS

Research area

The IMWM meteorological station in Kielce-Suków is located southeast of the Kielce city center, in the village of Suków, within the Świętokrzyskie Voivodeship. The station lies at an elevation of approximately 260 m a.s.l. on the edge of a loess upland, in an open area that ensures the proper exposure of instruments in accordance with World Meteorological Organization (WMO) standards. This setting provides high representativeness for the climatic conditions of the Świętokrzyskie region, particularly for suburban and agricultural landscapes (Fig. 1). According to the physical-geographical regionalization of Poland by Jerzy Kondracki (2002), the Kielce-Suków station is situated within the Polish Uplands province, the Małopolska Upland subprovince, and the Kielce Upland macroregion, specifically in the Świętokrzyskie Mountains mesoregion. This area is characterized by a diverse landform structure dominated by hills, slopes, and river valleys. The region also exhibits substantial geological variability, with sedimentary rocks—primarily limestones, marls, sandstones, and Paleozoic shales—prevailing. The presence of complex tectonic structures further contributes to local microclimatic differentiation.

The climate of the Świętokrzyskie region, including the area surrounding Kielce, is shaped by both its geographical setting and morphological features. It reflects characteristics of a temperate transitional climate, influenced by oceanic and continental air masses. Annual precipitation generally ranges from 600 to 750 mm, and the mean annual air temperature is approximately 7–8°C, although an upward trend has been observed in recent decades (Lorenc 2005; Dubicka et al. 2020). The Kielce Upland tends to be slightly cooler than the adjacent lowlands, which is associated with its elevation, forest cover, and differences in slope exposure.

The significance of the Kielce-Suków station as an observational site stems from its location in a transitional zone between lowland and upland areas, as well as from its extensive measurement record, which enables long-term climate analyses. Data collected at this station are widely used in meteorological and climatological research and have practical applications in hydrology and agriculture (Farat et al. 2010; Ziernicka-Wojtaszek 2019).

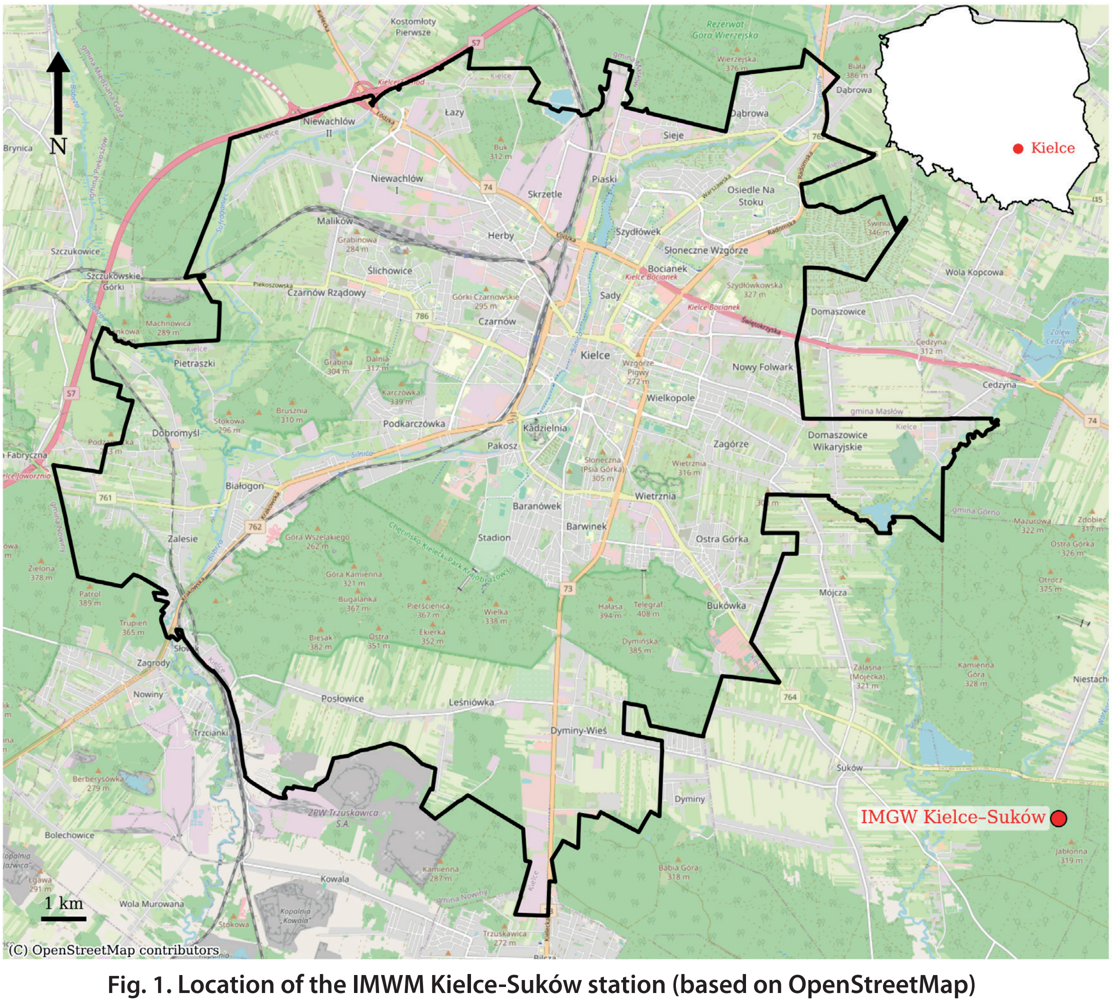

Fig. 1. Location of the IMWM Kielce-Suków station (based on OpenStreetMap)

Methods

The analysis of climatic conditions in the Kielce region was based on measurement data from the IMWM Kielce-Suków station, covering the multi-year period 1966–2024. Three fundamental meteorological elements were examined: air temperature, total precipitation, and the occurrence and depth of snow cover. To evaluate thermal conditions, the classification proposed by Lorenc and Bogucka (1996) was applied, enabling each calendar month to be assigned to one of eleven thermal classes according to deviations of monthly temperature from the mean value in the reference period. The baseline period was defined as the multi-year interval 1966–2023. This classification provides a systematic framework for assessing thermal anomalies on both monthly and seasonal scales (Table 1).

For borderline values, rounding to one decimal place was applied. The classification allows for the identification of thermal trends and the detection of extreme months, such as cold spells or heatwaves.

Annual and monthly precipitation totals were classified using a statistical approach based on percentiles derived from the distribution of values for the multi-year period 1966–2023. Five humidity classes were adopted, following methodologies commonly used in studies on the climate of Poland (Dubicka et al. 2020; Degirmendžić et al. 2004) (Table 2).

This classification allows for determining the frequency of occurrence of abnormally dry or wet years or months, which is important in the analysis of drought or flood risks.

Snow cover was analyzed based on daily observations of snow depth (in cm) and the number of days with snow cover recorded at the Kielce-Suków station. According to the guidelines of hydrometeorological stations, snow cover is recorded when the ground area surrounding the station is covered by snow over more than 50% of its surface. The snow cover is considered persistent if it remains for at least one month, with interruptions not exceeding three consecutive days. The analysis included the number of days per year with snow cover ≥1 cm, the average snow depth during the winter season (December–March), the maximum annual snow depth, and the dates of the onset and disappearance of persistent snow cover. Additionally, to identify seasonal changes, the average dates of the first and last snow cover in the season, as well as the duration of snow cover (both continuity and total number of days) were determined.

The data were analyzed with respect to long-term trends, inter-seasonal variability, and relationships with thermal and precipitation conditions. Basic descriptive statistics and trend analysis (linear regression) were applied for selected climate parameters.

The detection of heatwaves in this study follows the approach outlined by Perkins and Alexander (2013), which defines heatwaves as periods of at least three consecutive days (or months in the aggregated data) with temperatures exceeding a specific threshold based on historical climatology. Thresholds are typically set using percentile-based metrics (e.g., the 90th or 95th percentile of daily or monthly temperatures) to capture extreme thermal events relative to local climate variability.

Droughts are identified by consecutive months with precipitation below a critical percentile threshold (commonly the 25th percentile), indicating prolonged dry conditions. This percentile-based method ensures that drought definitions are sensitive to regional climate norms and variability.

Table 1. Thermal classification according to Lorenc and Bogucka (1996)

Thermal category	Condition of annual temperature relative to mean and standard deviation (SD)
Extremely warm	Tannual > Tmean + 2.5 SD
Anomalously warm	Tmean + 2.0 SD < Tannual ≤ Tmean + 2.5 SD
Very warm	Tmean + 1.5 SD < Tannual ≤ Tmean + 2.0 SD
Warm	Tmean + 1.0 SD < Tannual ≤ Tmean + 1.5 SD
Slightly warm	Tmean + 0.5 SD < Tannual ≤ Tmean + 1.0 SD
Normal	Tmean – 0.5 SD ≤ Tannual ≤ Tmean + 0.5 SD
Slightly cold	Tmean – 1.0 SD ≤ Tannual < Tmean – 0.5 SD
Cold	Tmean – 1.5 SD ≤ Tannual < Tmean – 1.0 SD
Very cold	Tmean – 2.0 SD ≤ Tannual < Tmean – 1.5 SD
Anomalously cold	Tmean – 2.5 SD ≤ Tannual < Tmean – 2.0 SD
Extremely cold	Tannual < Tmean – 2.5 SD

Table 2. Precipitation classification

Humidity category	Range (percentiles)
Very dry	≤ 10th percentile
Dry	11th –25th percentile
Normal	26th –75th percentile
Wet	76th –90th percentile
Very wet	≥ 91st percentile

This combined methodology provides a robust framework to analyze the frequency, duration, and intensity of heatwaves and droughts over time, facilitating the assessment of climate extremes and their potential impacts.

Long-term trends were evaluated using linear regression, with the slope parameter indicating the rate of change per year. The statistical significance of trends was assessed using Student's t-test for regression slopes and Kendall's tau test for monotonic trends, with p-values < 0.05 considered significant. All computations and visualizations were performed in R version 4.3.1 (R Core Team, 2023) using the *trend and ggplot2* packages.

To complement the station data, ERA5 reanalysis data were downloaded from the Copernicus Climate Change Service (C3S) Climate Data Store (CDS) (Hersbach et al. 2020), covering the period 1981–2023. ERA5 provides global estimates of meteorological variables at a horizontal resolution of approximately 31 km, allowing for comparison between local observations and large-scale reanalysis products. This comparison was performed to evaluate how well global datasets reproduce regional climate patterns and to assess the consistency of observed temperature and precipitation trends.

RESULTS

Based on the conducted research and analysis of meteorological data for the period 1966–2023, it was found that the average annual air temperatures exhibit a clear upward trend (Fig. 2). At the beginning of the observation period (1960s), the average temperature values ranged around 6–8°C, whereas in the last two decades, the average annual temperatures have consistently exceeded 8°C, reaching local maxima in 2018 (9.38°C), 2019 (9.73°C), and 2023 (9.58°C). This phenomenon indicates progressive climate warming in the Kielce region, consistent with global climate trends observed worldwide.

Based on the analysis of monthly average air temperature values from 1966 to 2023, conducted according to the thermal classification by Lorenc and Bogucka (1996), a detailed distribution of the frequency of occurrence of individual thermal classes was obtained (Fig. 3). This summary reflects the scale of thermal variability in the region and enables the identification of long-term climatic trends.

During the analyzed 58-year period (1966–2023; 696 months), the largest number of months was classified as thermally normal — a total of 275 months (39.5%). The next most frequent categories were slightly warm months (110 months, 15.8%) and slightly cold months (96 months, 13.8%), confirming the predominance of moderate temperature conditions characteristic of Poland's transitional climate.

Warm and very warm months occurred a total of 96 times (13.8%), while warm anomalies (anomalously and extremely warm months) were recorded in 11 cases (1.6%). In contrast, cold and very cold months appeared 88 times (12.6%), and cold anomalies (anomalously and extremely cold months) occurred in 20 months (2.9%).

On an annual scale, most years were also classified as thermally normal (22 years). Slightly cold and slightly warm years were recorded 9 and 8 times, respectively, while warm and very warm years occurred 5 and 4 times. The coldest categories — cold and very cold years — appeared 3 and 4 times, respectively, whereas thermal anomalies (anomalously cold and anomalously warm years) were rare, occurring only in three cases in total (two anomalously cold and one anomalously warm year).

Basic statistics were calculated for N-month periods:

• **slope** — the average annual change in the number of months within a given thermal class; a positive slope indicates an increasing number of months in that class, while a negative slope indicates a decreasing number of months;

• **p-value** (statistical significance test of the trend); $p < 0.05$ means the trend is statistically significant, $p \geq 0.05$ means there is insufficient evidence to confirm the trend;

• R^2 (coefficient of determination) indicates how well the linear model explains data variability (values range from 0 to 1); values close to 1 indicate a good fit, and values close to 0 indicate a poor fit.

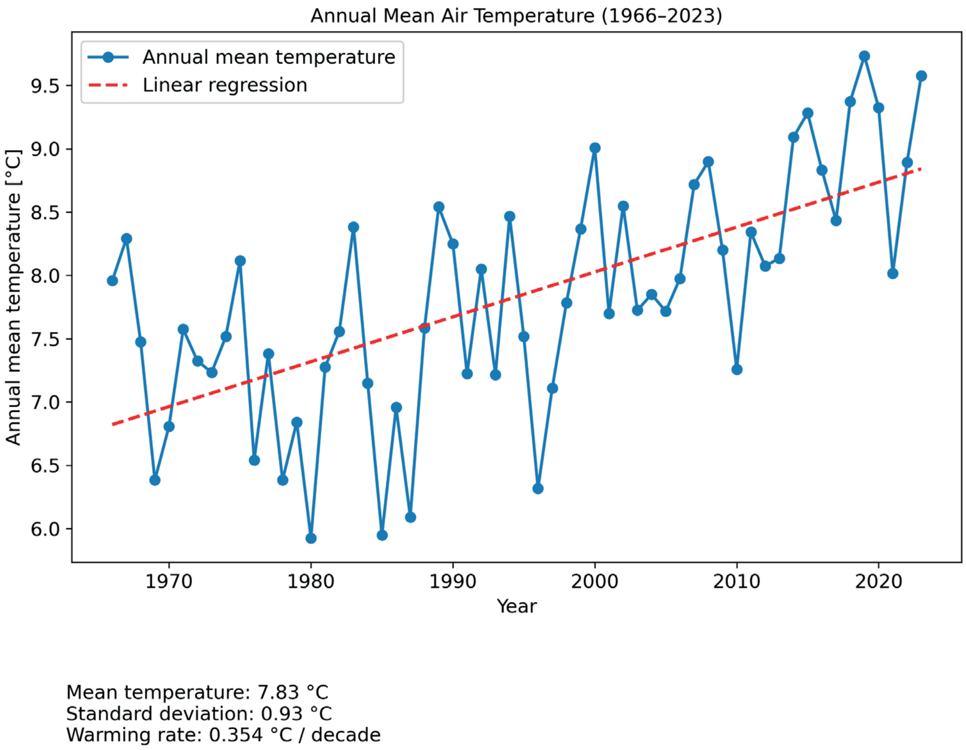

Fig. 2. Changes in the average annual air temperature values

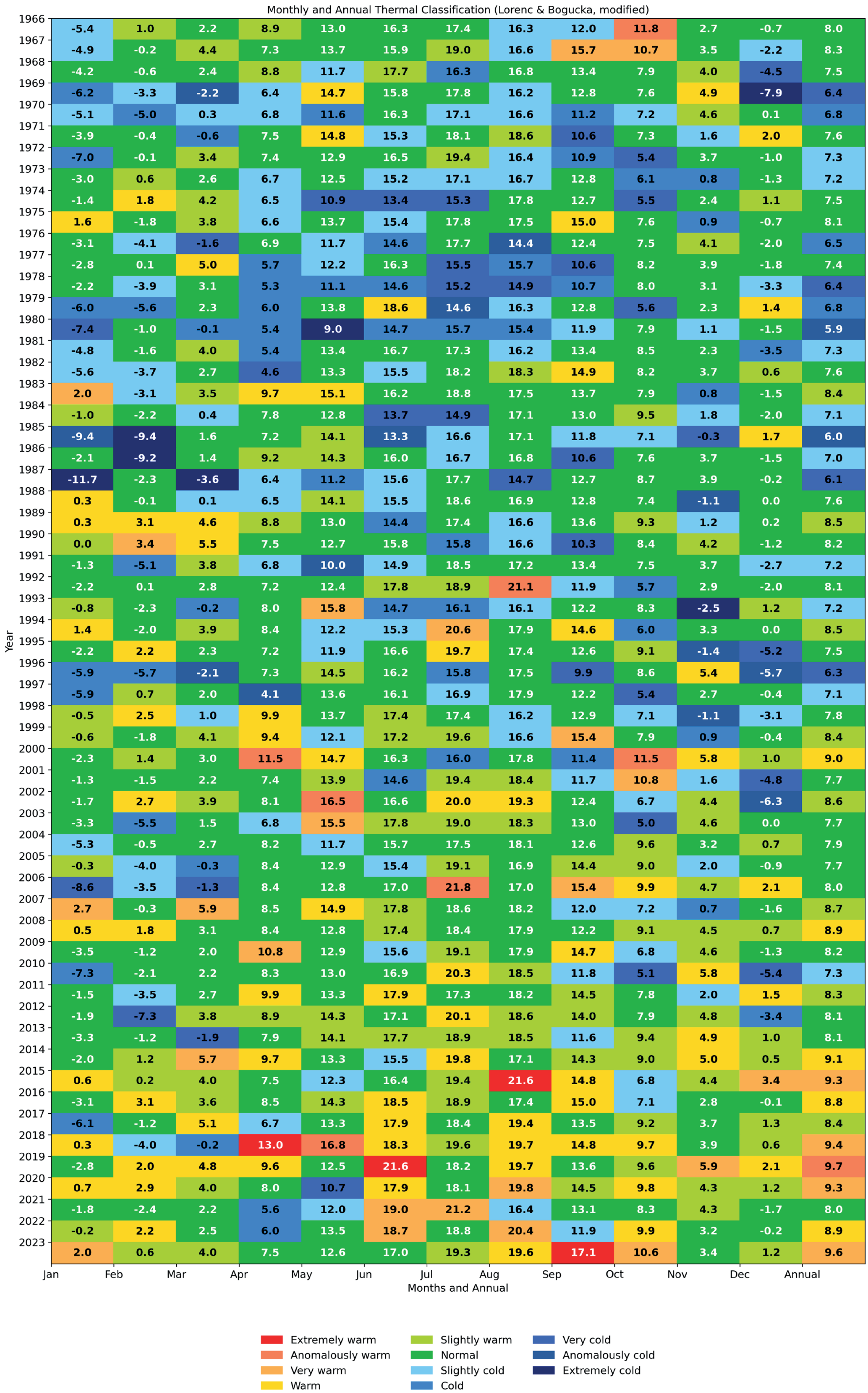

Fig. 3. hermal classification according to Lorenc and Bogucka (1996)

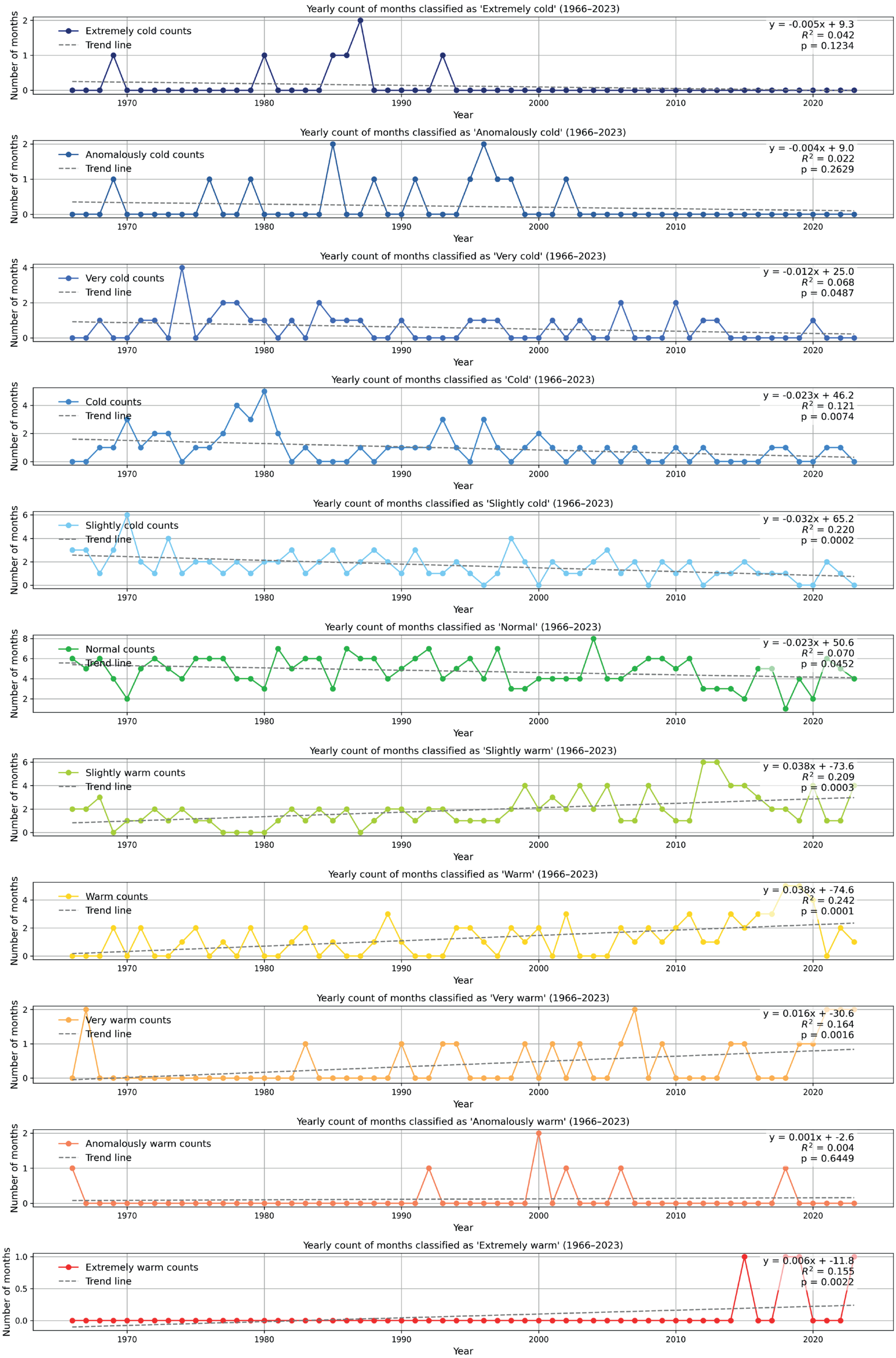

Fig. 4. Changes in the occurrence of individual thermal classes over the studied multi-year period

Based on the analysis of trends in individual thermal classes, a clear shift in the frequency of occurrence of months with different thermal characteristics was observed throughout the study period (Fig. 4, Table 3). Within the colder classes (from "very cold" to "slightly cold"), statistically significant decreasing trends were found, indicating a reduction in the frequency of cold months. The strongest negative trend occurred in the "slightly cold" class (slope = –0.032, p = 0.0002, R^2 = 0.22), meaning that such months have become increasingly rare over time.

In contrast, the warm classes ("slightly warm," "warm," "very warm," and "extremely warm") exhibit statistically significant positive trends, reflecting an increase in the frequency of warmer-than-normal months. The strongest positive trend was observed in the "warm" class (slope = 0.038, p = 0.0001, R^2 = 0.242), while a similarly significant but slightly weaker trend was found for the "slightly warm" class.

The extreme classes ("anomalously cold" and "anomalously warm") show no significant trends, suggesting that despite the overall warming tendency, the occurrence of thermally extreme months remains irregular and variable.

Overall, the results clearly indicate a systematic warming of the climate in the analyzed period, manifested by a decrease in the frequency of cold months and an increase in the occurrence of warm months.

Analysis of annual precipitation totals revealed significant variability between individual years, with values ranging widely from 439 mm (in 1982) to nearly 1000 mm (in 1966). Unlike temperatures, the precipitation totals do not show a clear increasing or decreasing trend over the studied period. Average annual precipitation generally remains within the range of 500 to 750 mm, which is characteristic of a temperate climate, where precipitation dynamics are strongly influenced by variable atmospheric factors and local meteorological conditions (Fig. 5).

The obtained results indicate that, despite the observed global warming trend, precipitation in the Kielce region does not show a similar tendency in quantitative changes over the studied period. The limited predictability of annual precipitation totals highlights the need for further detailed studies considering seasonal and long-term fluctuations and their impact on local ecosystems and water management.

Table 3. Characteristics of individual thermal classes

Thermal class	N	Slope	p-value	R^2	Interpretation
Extremely cold	7	-0.005	0.1234	0.042	No significant trend
Anomalously cold	13	-0.004	0.2629	0.022	No significant trend
Very cold	33	-0.012	0.0487	0.068	Significant but weak decreasing trend, poor fit
Cold	55	-0.023	0.0074	0.121	Significant decreasing trend, moderate fit
Slightly cold	96	-0.032	0.0002	0.22	Significant decreasing trend, moderate fit
Normal	275	-0.023	0.0452	0.07	Significant decreasing trend, poor fit
Slightly warm	110	0.038	0.0003	0.209	Significant increasing trend, moderate fit
Warm	73	0.038	0.0001	0.242	Significant increasing trend, moderate fit
Very warm	23	0.016	0.0016	0.164	Significant but weak increasing trend, moderate fit
Anomalously warm	7	0.001	0.6449	0.004	No significant trend
Extremely warm	4	0.006	0.0022	0.155	Significant but weak increasing trend, moderate fit

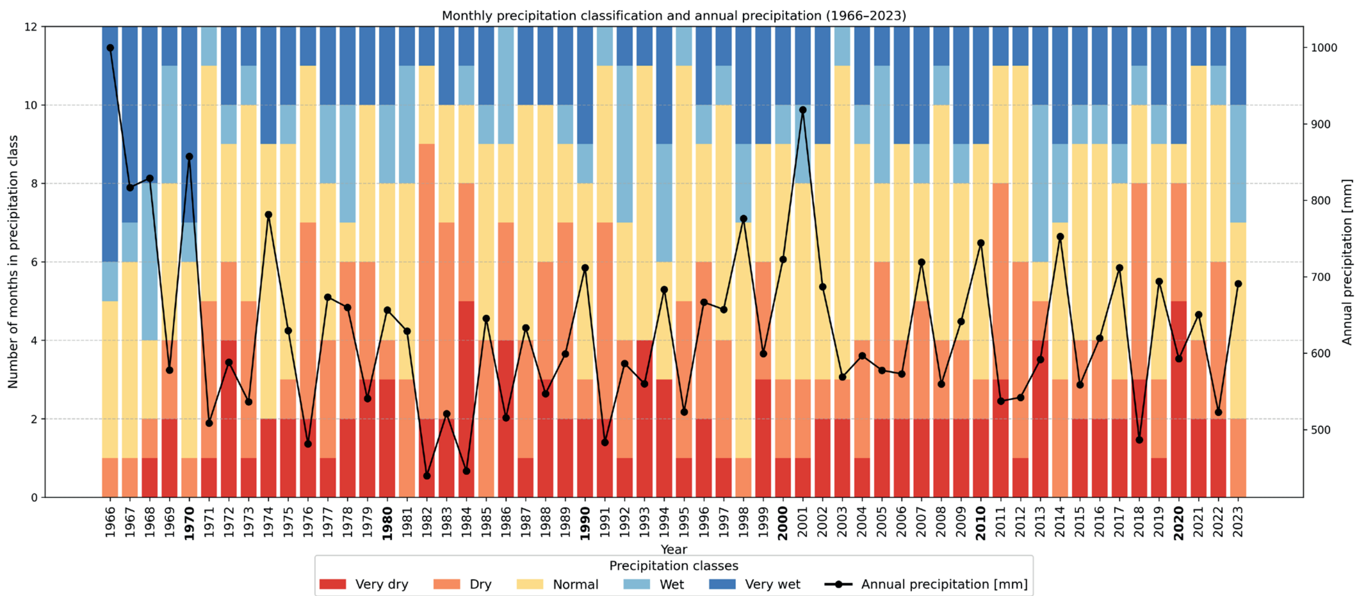

Fig. 5. Precipitation classification during the studied period

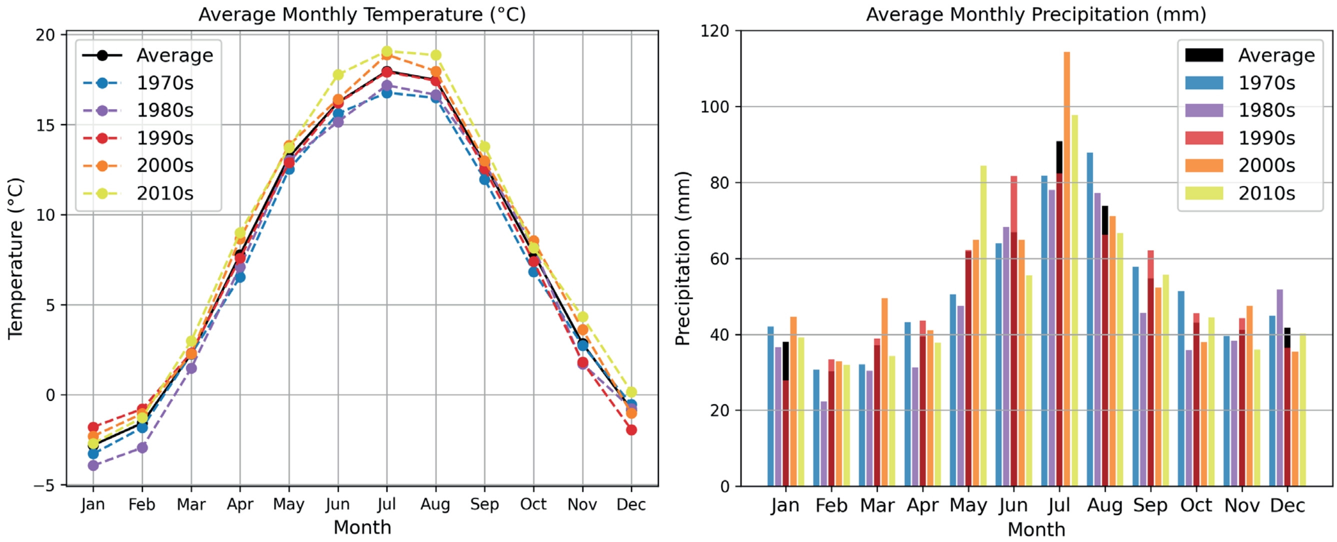

Fig. 6. Trends of temperature and precipitation totals in individual decades of the multi-year period

Based on the course of the average monthly air temperature and precipitation totals (Fig. 6), the following features can be observed:

• The greatest temperature increase occurred in January (+5.32°C), August (+2.57°C), and March (+2.08°C).

• Winter warming is evident — temperatures shifted from distinctly negative values in the 1960s to positive values by 2020.

• Significant summer warming.

• Spring and autumn show smaller changes, sometimes even stability or slight cooling (April, May).

• No clear trend in precipitation — rainfall does not show a systematic increase or decrease as distinct as temperature.

• High variability between decades — for example, June and July in 1960 had very high precipitation, which later significantly decreased.

• Summer precipitation (June–August) exhibits the greatest differences between years, which may indicate increasing irregularity (e.g., storms, droughts).

A particularly dynamic pattern is observed in the number of days with snow cover over the analyzed period, 1966–2024 (Fig. 7).

The analysis indicates a significant and consistent decline in the number of days with snow cover during the study period. Although the linear trend does not account for all variability in the data—which is expected under climatic conditions influenced by multiple factors—statistical tests confirm that the decrease in snow cover days is a real and robust phenomenon (τ = -0.306). On average, the number of days with snow cover decreases by approximately 0.61 days per year. From the beginning to the end of the studied period, the number of snow-cover days has declined by over 78%.

The long-term analysis of snow cover data from 1966 to 2024 reveals substantial interannual variability and a clear downward tendency in both snow persistence and depth. The number of days with snow cover (≥1 cm) varied considerably between years, ranging from over 100 days in particularly snowy winters (e.g., 1969, 1970, 1996, 2006, 2010) to fewer than 10 days in exceptionally mild winters such as 2020 (Table 4)

The average snow depth during the winter season (December–March) also shows a marked decline over the study period. In the late 1960s and early 1970s, average values frequently exceeded 5–10 cm, with extreme seasons such as 1970 and 2006 reaching 15–20 cm. In contrast, since the 2010s, the mean snow depth has often remained below 3 cm, reflecting milder winter conditions and shorter snow accumulation periods.

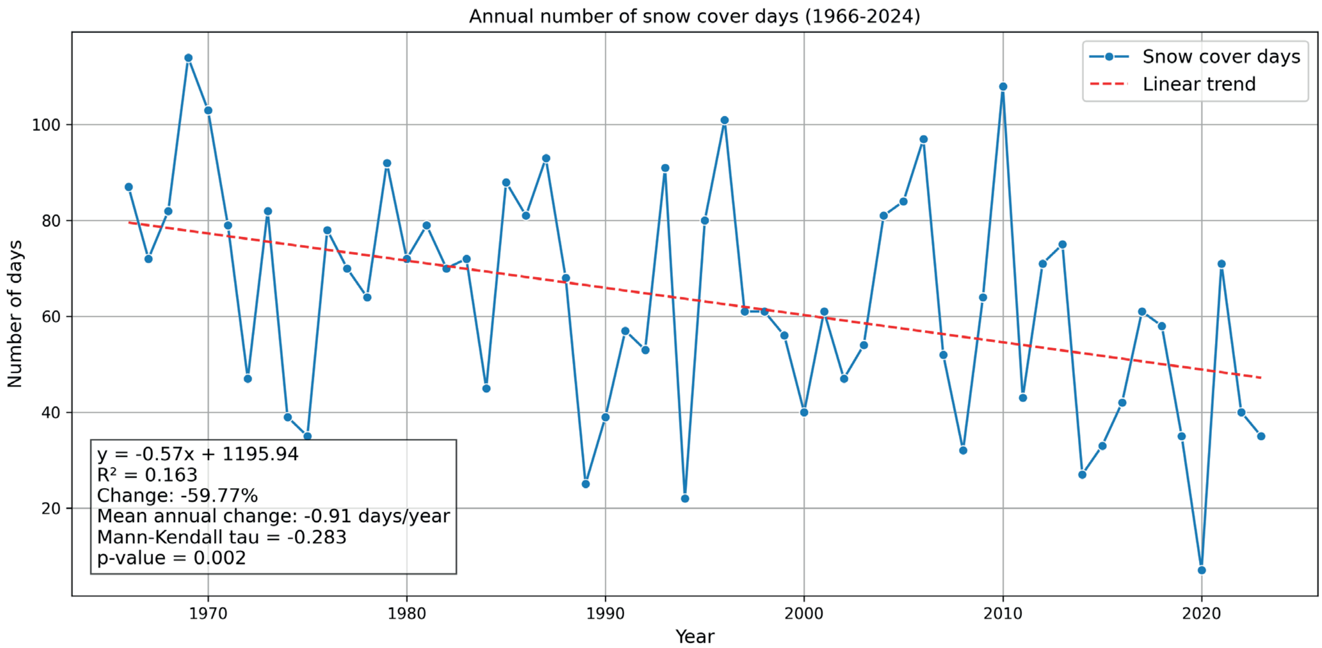

Fig. 7. Number of days with snow cover in individual years over the period 1966–2024

Table 4. Statistical characteristics and long-term trends of snow cover parameters (1966–2024)

Parameter	Mean	Min (Year)	Max (Year)	Std. Dev.	Trend per decade
Days with snow cover (≥1 cm)	62.73	7 (2020)	114 (1969)	24.05	-6.05
Average snow depth in winter (Dec–Mar)	4.84	0.07 (2020)	23.4 (1970)	4.5	-0.52
Maximum annual snow depth	20.36	4.0 (2020)	55.0 (1970)	9.35	-0.93
Persistent snow cover duration (≥30 days)	25.75	0.0 (1971)	96.0 (1969)	29.87	-5.13

The mean annual number of snow-cover days was approximately 63, showing high interannual variability (ranging from 7 days in 2020 to 114 days in 1969). The trend analysis confirms a consistent decrease in both snow duration and depth, with the decline being particularly evident after the year 2000.

The average winter snow depth was 4.84 cm, and the maximum annual snow depth reached an average of 20.36 cm, with both parameters exhibiting a marked reduction over time—especially in the most recent decades. Periods of persistent snow cover (lasting at least 30 consecutive days) were regularly observed from the 1960s through the early 1990s, often extending from early January to late February or even into March (e.g., 1970, 1987, 1996, 2006, 2010). In recent decades, such prolonged snow periods have become rare or completely absent, indicating a fundamental shift in the local snow regime.

The heatmap reveals clear seasonal patterns in the temperature trends associated with different precipitation classes (Fig. 8). The strongest and most coherent changes occur during the summer (July–September) and late-autumn (November) months, whereas trends in the winter and early-spring period remain weak or statistically insignificant. Most precipitation classes—particularly wet and moderately dry months—exhibit predominantly positive slopes, indicating a systematic warming during the second half of the year. Notable contrasts are evident among the classes: for example, in the "very dry" category, July shows a strong negative trend, while November displays an exceptionally pronounced positive trend. This variability suggests that the temperature response to precipitation regime is nonlinear and likely driven by interactions between atmospheric circulation, cloud cover, and local water-energy balance.

Overall, the results highlight an intensifying warming signal in late summer and autumn, accompanied by substantial variability across extreme precipitation conditions.

The analysis of heatwaves and drought occurrences across decades from the 1970s to the present reveals clear climate changes in the Kielce region (Fig. 9). In terms of heatwaves, none were recorded in the 1970s, indicating that extremely warm years were very rare or absent during this period. The first heatwaves appeared in the 1980s and 1990s, but they were still relatively infrequent, occurring in about 20% of the years. In the 2000s, there was a noticeable increase in heatwave frequency, reaching 40% of years. The most significant rise occurred in the last decade—the 2010s—when heatwaves were present in 60–70% of the years, clearly signaling a strong warming trend and a growing number of extreme heat events in the region.

Regarding droughts, their frequency in the 1970s was relatively high, ranging from 25% to 50% of years, indicating notable precipitation deficits already during these decades (Fig. 9). The peak drought frequency occurred in the 1980s and 1990s, affecting 50–70% of the years, which reflects very frequent dry conditions. However, in the 2000s, drought frequency sharply declined to about 10%, possibly due to climatic variability or increased rainfall during that period.

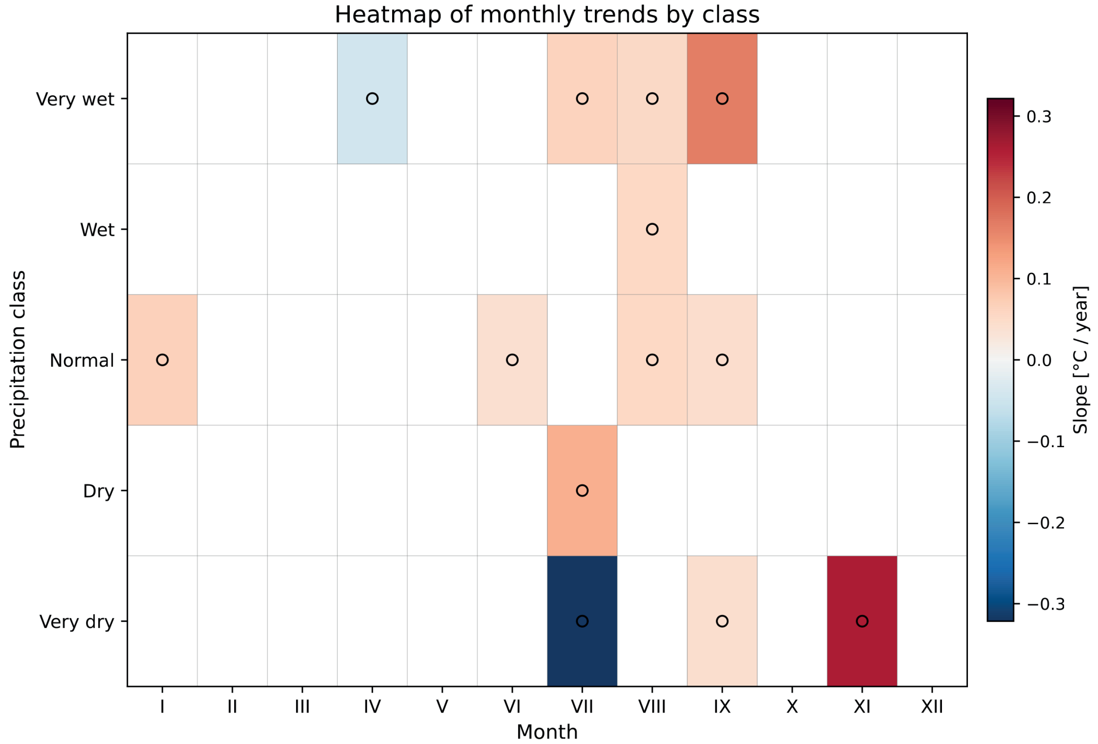

Fig. 8. Heatmap: the circle marker inside selected grid cells indicates that the trend is statistically significant at the adopted significance level (typically $p < 0.05$)

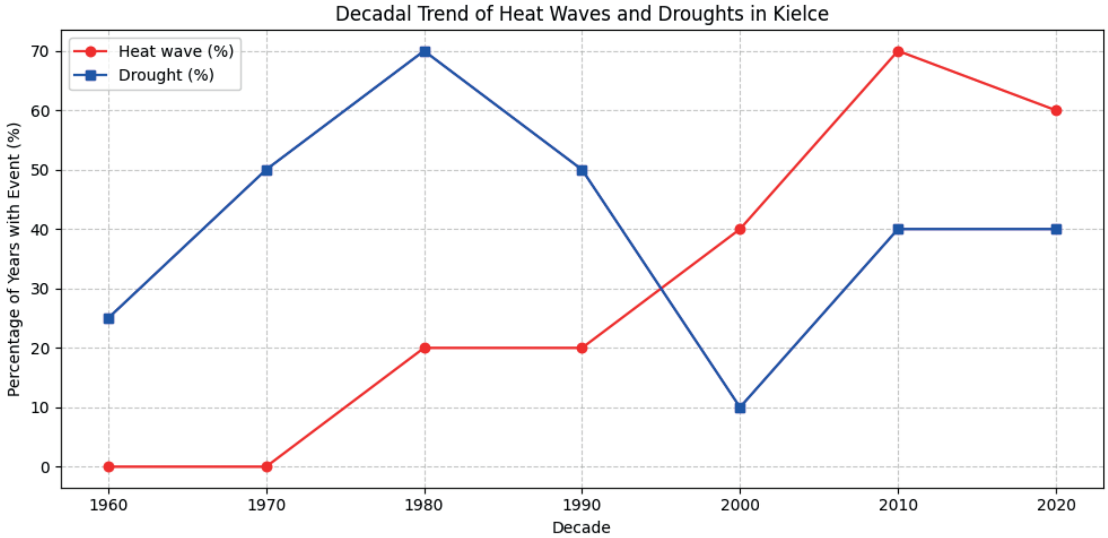

Fig. 9. Occurrence of heatwaves and droughts in Kielce (1960–2020)

Comparing both phenomena, the early decade (1970s) experienced low heatwave frequency but relatively frequent droughts. Since the 1980s, there has been a marked increase in heatwaves, especially pronounced in the last two decades. Drought frequency has been more variable, peaking in the 1980s, decreasing in the 2000s, and increasing again in recent years. The 2010s are characterized by frequent co-occurrence of heatwaves and droughts, signaling growing climatic stress on agriculture, ecosystems, and public health.

The applied forecasting approaches — the linear trend model and the ARIMA model — exhibit a high degree of consistency in projecting the mean annual air temperature for the year 2030 (Fig. 10). The obtained estimates are 9.14°C for the linear model and 9.16°C for the ARIMA model. This minimal difference indicates that the temperature dynamics in the analyzed time series are predominantly governed by a stable and unidirectional long-term warming trend.

The ARIMA model, which incorporates the autoregressive structure and differencing components in addition to the trend, yields a slightly higher forecast. This can be attributed to its ability to account for short-term fluctuations and the memory of the process, potentially amplifying the upward signal to a small extent. Nevertheless, the difference of approximately 0.02°C is statistically negligible given the length of the series and the inherent forecast uncertainty.

The convergence of both models strengthens the reliability of the estimated warming rate in the study area. The projected values clearly suggest a continuation of the long-term upward temperature trend through 2030, aligning with broader observations of climatic warming at both national and global scales.

The Mann-Kendall test results indicate a clear increasing trend in daily mean temperature at the Kielce station (IMGW), with a Sen slope of approximately 0.464 °C per decade. ERA5 reanalysis data over the same period also show a statistically significant increasing temperature trend, with a slightly smaller Sen slope of 0.428 °C per decade. These results suggest that ERA5 captures the general warming signal observed in station measurements, though the station data indicate a marginally stronger warming.

For precipitation, the trends are less pronounced. The IMGW data show a weak decreasing trend, while ERA5 indicates no significant trend. The Sen slopes are effectively zero for both datasets, confirming that annual precipitation

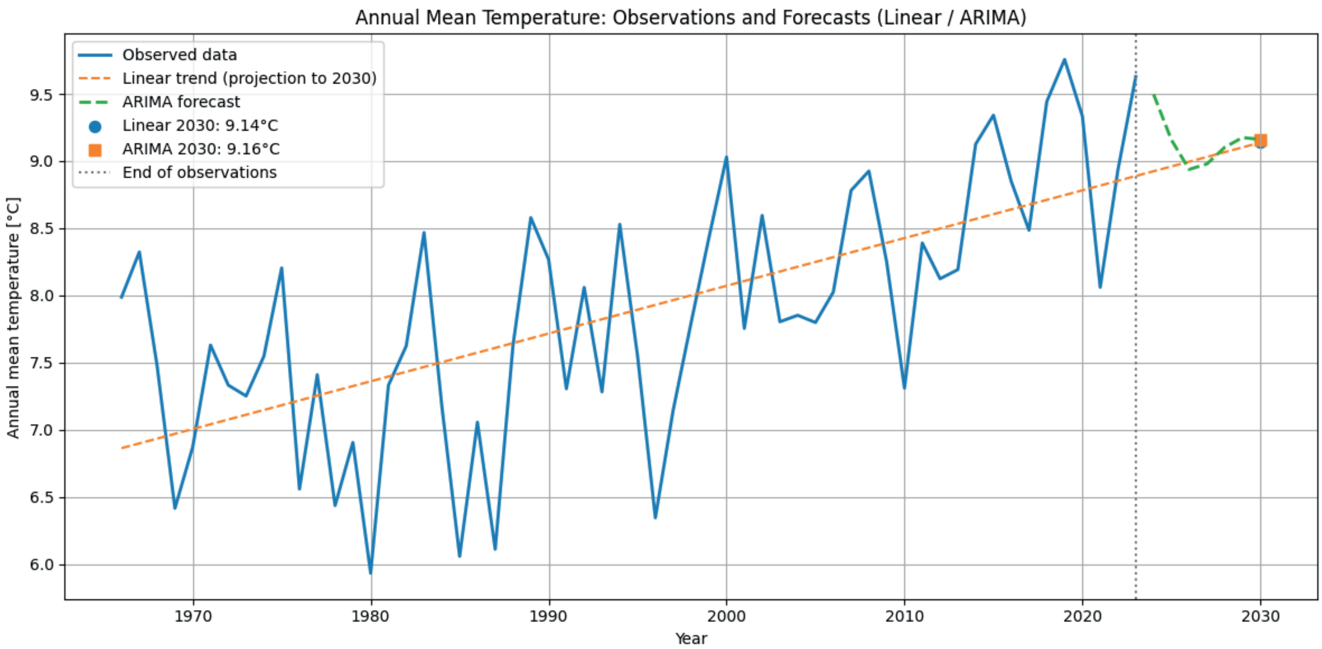

Fig. 10. Annual mean temperature trends with linear projection and ARIMA forecast to 2030 based on historical observations

totals have remained relatively stable over the study period. This discrepancy may reflect the coarse spatial resolution of ERA5, which can smooth local variations, particularly for precipitation, whereas station measurements capture site-specific conditions more accurately.

Overall, the comparison demonstrates that ERA5 reanalysis provides a good representation of temperature trends at the local scale, but local precipitation patterns are less reliably reproduced. These findings highlight the value of combining long-term station observations with reanalysis data to assess regional climate changes, especially when considering impacts on agriculture and water resources.

DISCUSSION

The increasing trend of moisture deficit in Central and Southern Europe, driven by rising air temperatures and enhanced evapotranspiration, has been confirmed by Urban et al. (2022). One of the consequences of climate change is the disruption of the hydrological regime. Climate warming after 1988 has affected the depth of genetically diverse low flows in Polish rivers in different ways. Summer low flows — shaped by low or absent precipitation, high air temperatures, and elevated evaporation — generally deepened, especially in rivers located in central Poland. In contrast, warmer winters and more frequent mid-winter thaws increased runoff in many rivers, leading to the shallowing or even disappearance of winter low flows (Wrzesińska and Wrzesiński 2023).

In recent decades in Poland, particularly in the Świętokrzyskie region, a clear increase has been observed in the frequency and intensity of heatwaves and drought periods, which heightens the risk of compound extreme events with complex environmental and socio-economic impacts. These phenomena pose serious threats to water resources, ecosystems, and public health (Ciupa and Suligowski 2020; Szwed et al. 2023). As emphasized by Ciupa and Suligowski (2009), a key component of climate change adaptation is the development of small retention systems and improved water resource management, aimed at enhancing hydrological and ecological stability in both rural and urban areas. In Kielce, the water supply system is particularly sensitive to climate change, especially during droughts occurring in combination with high temperatures (UM Kielce, 2018). This vulnerability is linked to the formation of a shallow yet extensive depression cone near the Białogon groundwater intake, caused by intensive exploitation and a high share of impervious surfaces within its recharge zone. This intake supplies approximately 64% of the city's population. Simultaneously, water demand increases during heatwaves and droughts. Water shortages also strongly affect agriculture in the Świętokrzyskie region; in recent years, spring drought has impacted most cereal

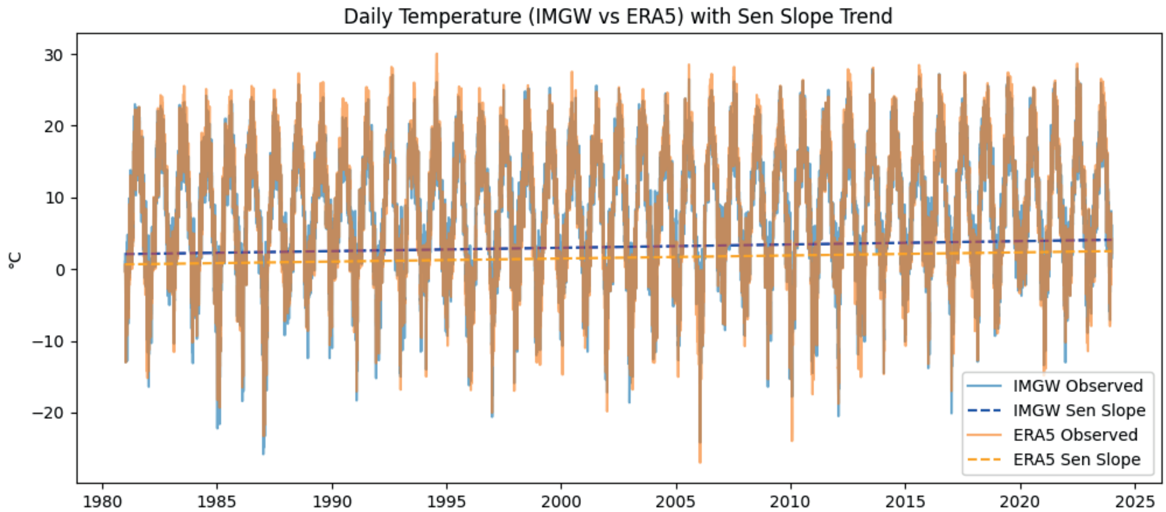

Fig. 11. Daily mean temperature in the Kielce region from IMGW station measurements (blue) and ERA5 reanalysis data (orange) for the overlapping period. Dashed lines represent the Sen Slope trends for each dataset, indicating a statistically significant warming trend in both datasets

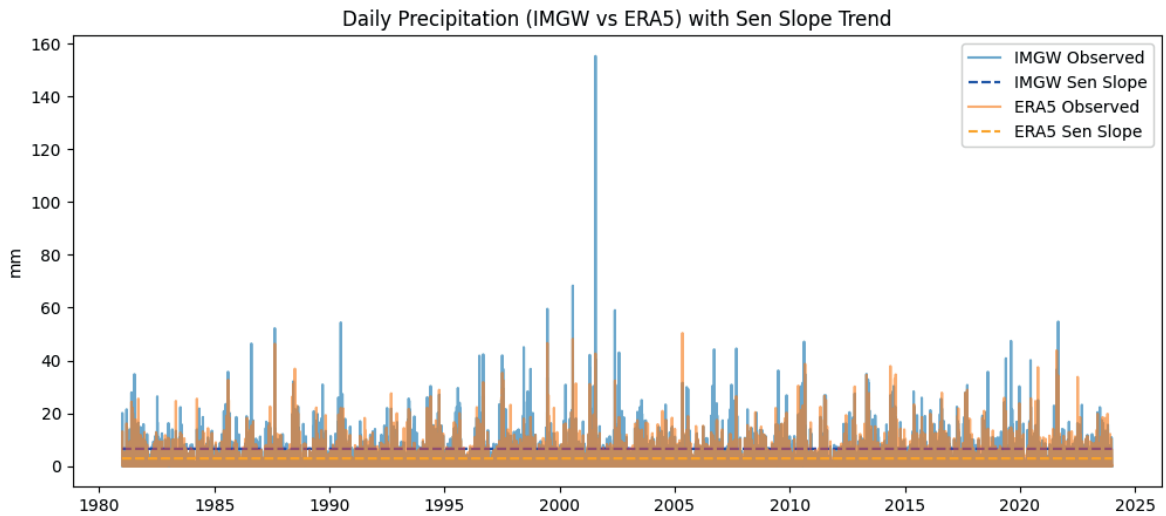

Fig. 12. Daily precipitation totals in the Kielce region from IMGW station measurements (blue) and ERA5 reanalysis data (orange). Dashed lines show the Sen Slope trends, indicating a weak decreasing trend in station data and no significant trend in ERA5 reanalysis

crops, shrubs, and fruit trees, causing yield losses of 30–50% (IUNG-PIB, 2024). In 2024, agricultural drought affected 68 out of 102 municipalities in the voivodeship.

Research by Ciupa and Suligowski (2020) highlights that urbanization, particularly in cities such as Kielce, significantly alters the hydrology of urban catchments. Differences in land use within the Silnica and Sufraganiec catchments influence both the speed and volume of surface runoff, thereby intensifying local heatwaves and increasing the risk of droughts and flash floods (Ciupa and Suligowski 2014a; 2014b). These hydrological changes also affect pollutant transport, placing additional stress on aquatic ecosystems (Ciupa and Suligowski 2020).

At the national scale, IMWM data show a steady increase in the number of days with maximum temperatures above 30°C (IMWM 2020). Combined with decreasing precipitation sums and longer dry spells, these changes contribute to the intensification of meteorological and hydrological droughts (Kundzewicz et al. 2018). Rising air temperatures strengthen evaporative demand, reducing water availability for agricultural and municipal purposes, particularly in low-retention regions such as Świętokrzyskie (Ciupa and Suligowski 2018).

The results of phenological analyses, indicating an advancement of certain seasons and an extension of the growing period, are consistent with observations from other regions of Poland and correspond with global trends in air temperature rise (Cleland et al. 2007; Tomczyk and Szyga-Pluta 2016). Phenological studies conducted by the Institute of Meteorology and Water Management – National Research Institute (IMWM) for the period 2007–2018 show a clear advancement in the onset dates of early spring and spring, as well as a slight delay in the beginning of autumn. For early spring, spring, and full spring, the onset advanced by 9–11 days relative to the 1951–1990 reference period, while the onset of autumn was delayed by 3 days. Consequently, the length of the growing season increased by approximately 12 days (Chojnacka-Ożga and Lorenc, 2019).

From a public health perspective, heatwaves are associated with increased hospitalizations and mortality related to cardiovascular and respiratory diseases, especially among vulnerable groups such as the elderly and children (EEA 2023). In Poland, an increase in heatstroke and other heat-related illnesses has been observed during periods of extreme heat (Szwed 2018).

The results obtained for the Kielce-Suków station correspond to warming trends recorded in other regions of Poland. Temperature statistics based on data from synoptic stations, calculated in accordance with the WMO Guidelines on the Calculation of Climate Normals (WMO-1203) for the 1991–2020 normal period, confirm the direction and magnitude of change observed in Kielce. The course of this trend varies according to local topographic and geographic conditions. Particularly valuable in this context are studies conducted within the Integrated Environmental Monitoring Network, which collects meteorological data representative of Poland's landscape zones, delineated according to the geoecosystem concept (Kostrzewski and Stach 1992).

Analyses of heatwaves and droughts in the monitoring network indicate a clear increase in the frequency of heatwaves in recent decades, consistent with global warming trends. In the 2010s and 2020s, heatwaves occurred in 60–70% of years, demonstrating a marked intensification of extreme heat events. Droughts remain a persistent climatic issue, with the highest frequency noted in the 1980s, followed by a decline and a moderate resurgence in recent years. The growing concurrence of heatwaves and droughts highlights an increasing risk of compound extreme weather events that pose significant threats to water resources, ecosystems, and public health. These findings underscore the need for effective adaptation strategies, enhanced water management, and improved preparedness measures to mitigate the impacts of these climatic hazards.

Long-term air temperature measurements at Integrated Environmental Monitoring base stations show an unfavorable trend of rising mean annual temperatures. A statistically significant upward trend ($p < 0.05$) was identified for 8 out of 11 stations with at least a 10-year measurement record: Wolin, Parsęta, Puszcza Borecka, Chełmno Lakeland, Kampinos, Łysogóry, Carpathian Foothills, and the Low Beskids. The average 10-year increase in mean air temperature is 0.71°C per decade. The highest trends, exceeding 0.7°C, were recorded at Wolin (1.28°C) and Kampinos (0.75°C), while the lowest values, below 0.5°C, were observed at the Chełmno Lakeland station (0.45°C).

A series of studies conducted in Poland indicate that warming is one of the most pronounced and statistically significant elements of climate change in the region, with particularly rapid temperature increases observed during the winter and summer months. Analyses covering dozens of meteorological stations have shown that the annual mean temperature in Poland is rising at a rate of approximately 0.2–0.3°C per decade, which is consistent with trends observed in many cities, including those in the central and southern parts of the country (Kejna and Pospieszyńska 2023; Kundzewicz et al. 2019). The observed temperature changes in Kielce align well with these nationwide patterns.

An important aspect of contemporary climate change is also the increase in the frequency and intensity of heat extremes. Studies by Wibig et al. (2009) demonstrated a clear rise in the number of hot days and tropical nights in Poland, especially after 1990. This trend is also characteristic of Eastern Europe, where heatwaves are occurring more frequently and lasting longer (Russo et al. 2015). The results from Kielce, indicating rising maximum temperatures, are consistent with this broader European pattern.

In contrast, precipitation variability and trends in Poland are considerably more spatially and seasonally diverse. Numerous studies have highlighted that, despite some upward trends in summer precipitation in certain parts of the country and downward trends during winter, the climatological signal of precipitation is weak and statistically unstable (Łupikasza 2010; Szwed 2018). For this reason, the lack of a clear direction of precipitation changes in Kielce aligns with the literature – many stations in Poland show a similar picture of high interannual variability and difficulty in identifying persistent trends.

Similarly, the observed shortening of snow cover duration in Kielce is a well-documented trend nationwide. Analyses conducted since the mid-20th century indicate a systematic reduction in the length of snow cover periods and a decrease in maximum snow depths across most regions of Poland, particularly in lowland areas (Falarz 2007). The reduction in snow cover is also a characteristic feature of climate change in Eastern Europe, associated, among other factors, with the rapid pace of winter warming and more frequent occurrences of temperatures crossing 0°C (Bulygina et al. 2011).

CONCLUSIONS

The analysis of long-term meteorological data from Kielce clearly documents significant climate changes in the Świętokrzyskie region. Thermally normal months remain the most common, but in recent decades, the frequency of warm and very warm months has increased, consistent with regional and national warming trends. Concurrently, the number of cooler months has declined, with the most pronounced decrease observed in the "slightly cold" class.

Long-term snow cover analysis (1966–2024) indicates a gradual reduction in both duration and thickness, with persistent snow cover (≥30 days) becoming increasingly rare after the 1990s. Winters are now shorter and less snowy, with more frequent thaw events, reflecting broader regional warming trends.

The results highlight an increasing co-occurrence of heatwaves and droughts, particularly since the 2010s, when heatwaves affected 60–70% of years. Droughts, while peaking in the 1980s, have reappeared recently. These trends indicate the region's growing exposure to compound climate extremes.

Importantly, these observed climatic changes have direct implications for regional vulnerability:

1. Water resources: Reduced snow cover and prolonged warm periods increase the risk of low river flows and groundwater depletion, stressing municipal and agricultural water supplies.

2. Agriculture: Rising temperatures and extended dry spells heighten the risk of crop losses, particularly for cereals, fruit trees, and shrubs.

3. Urban planning and infrastructure: Higher frequency of heatwaves and combined drought conditions demand adaptive strategies for urban water supply, stormwater management, and public health preparedness.

In summary, while the study confirms ongoing warming and declining snow cover in central Poland, the applied relevance is clear: proactive adaptation in water management, agriculture, and urban planning is essential to mitigate the impacts of these climate changes. Integrating these findings into regional policy and management strategies can help enhance resilience against increasing thermal and hydrological extremes.

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